

Distribution, Age, and Formation Mechanisms of Lunar Pits

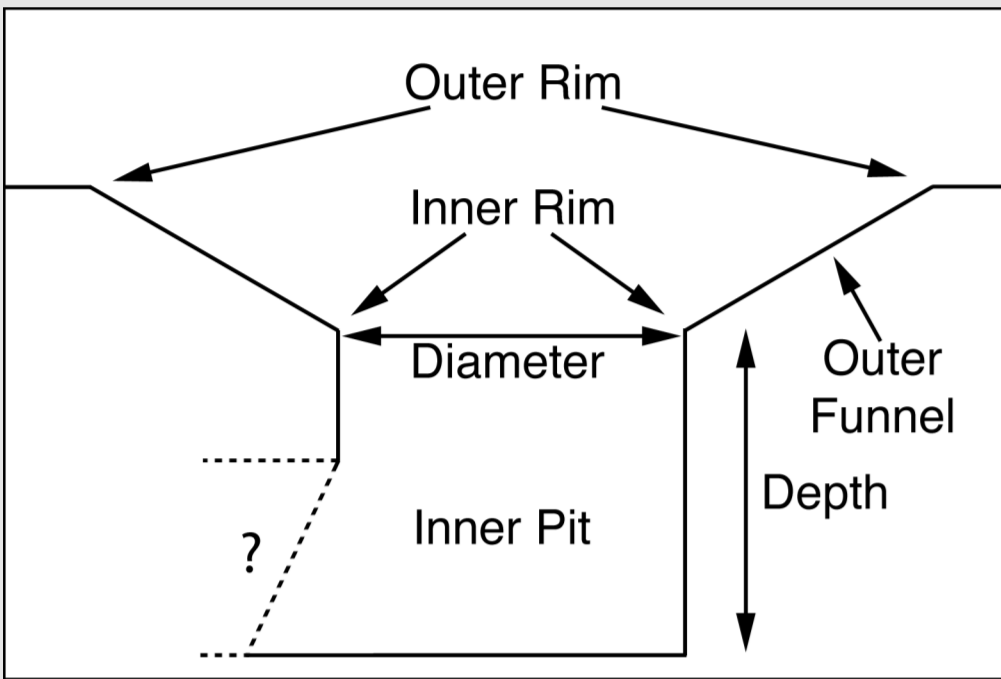
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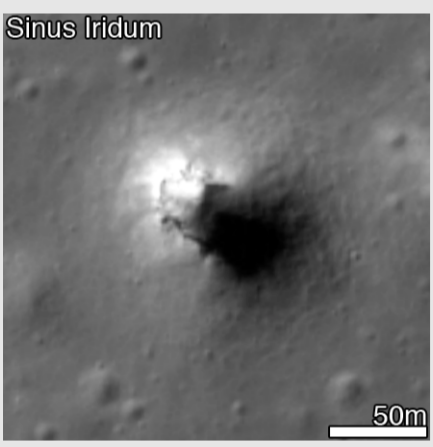
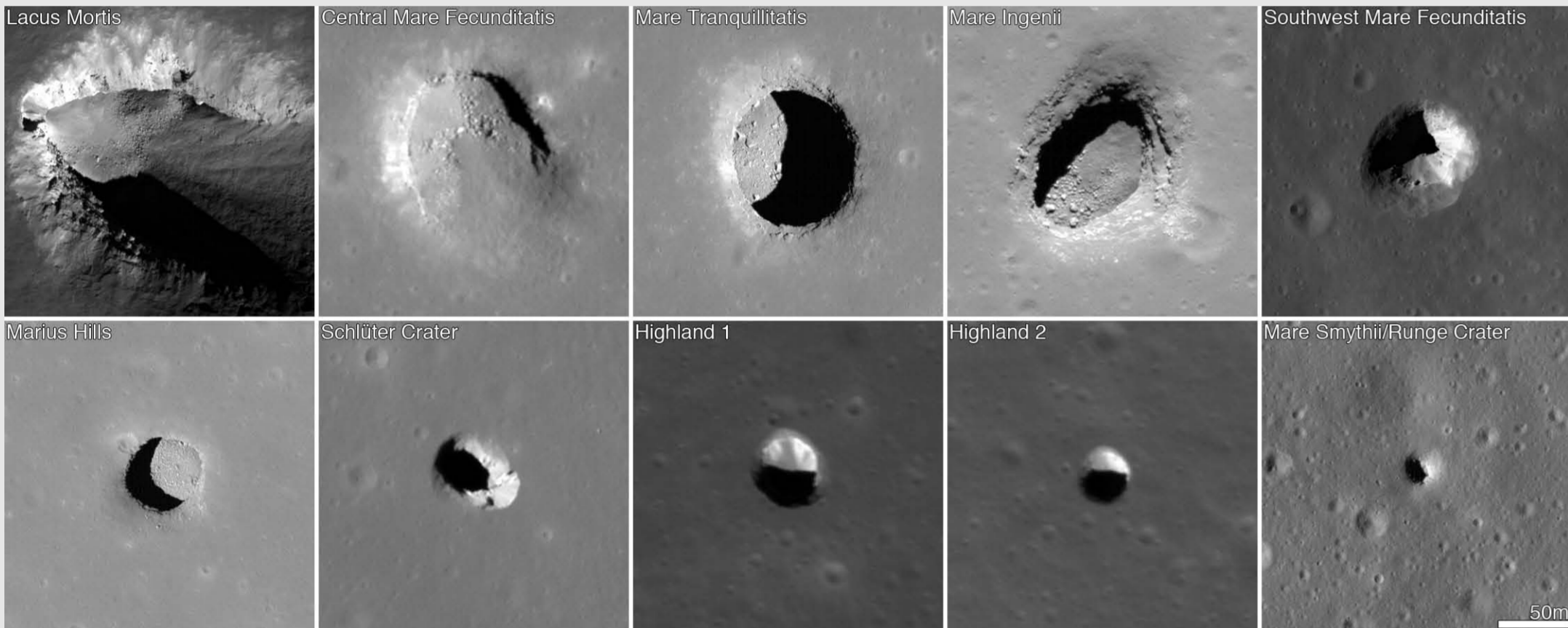
Introduction

Lunar pits, steep-walled collapse features, were first discovered in Kaguya images, with three pits discovered in 2009 and 2010 [1]. We have discovered over 200 additional pits using Lunar Reconnaissance Orbiter Camera images [2], some of which could provide access to sublunarean void spaces. Nine of these pits were found in maria, and two were found in highlands terrain, while the rest were found in impact melt deposits of 30 Copernican craters. Pits are useful for examining the history of mare emplacement, studying melt flow within impact melt ponds, and could provide shelter for future surface explorers.

Pits range in diameter from ~900 m down to less than 5 m, with a median diameter of 16 m, and a median depth of 7 m. Mare pits tend to be larger than the impact melt pits that dominate these statistics, with the majority of mare pits being >40 m in diameter and >30 m deep.

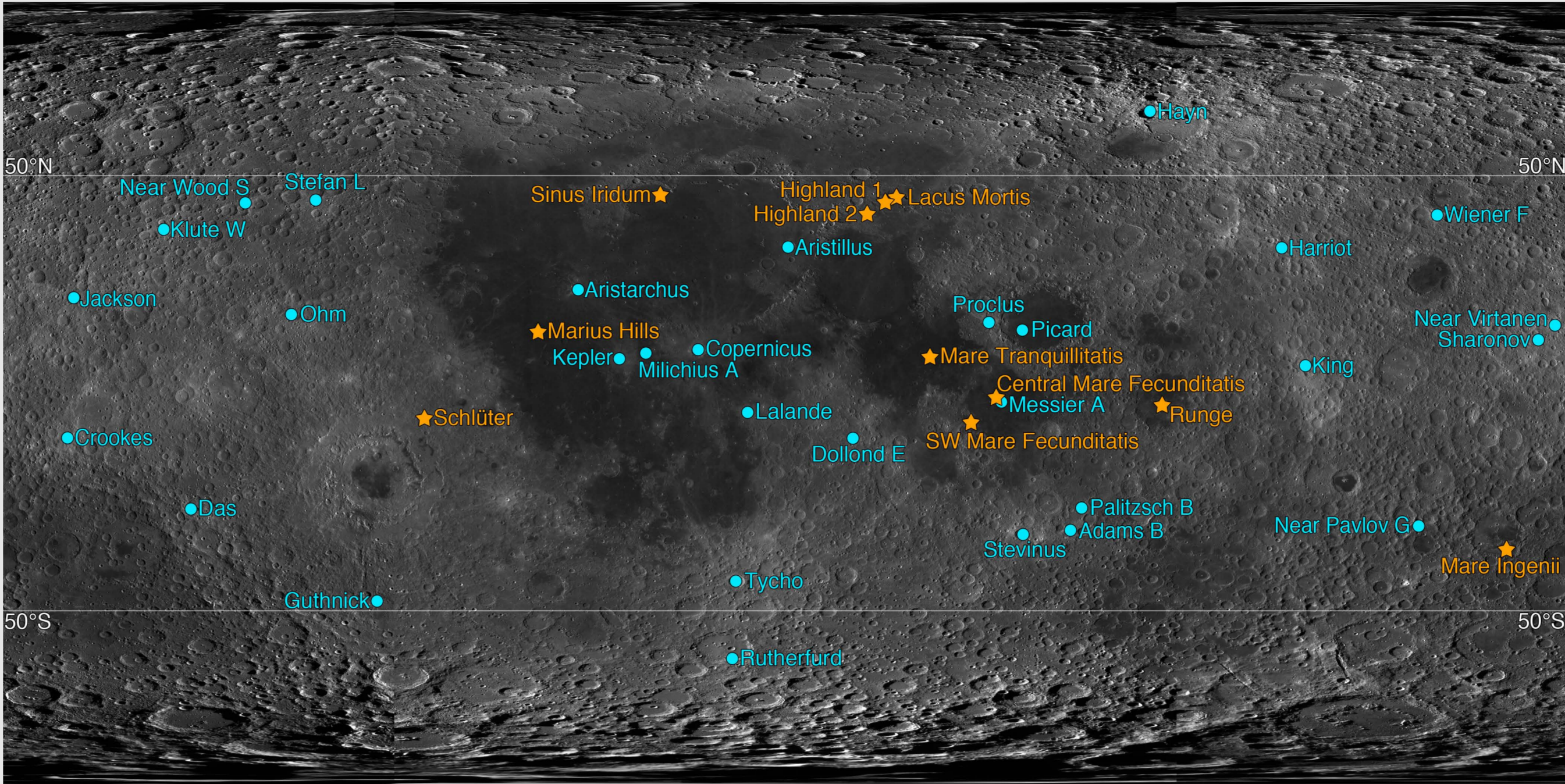


Anatomy of a pit: Pits generally have two main sections, shown here in cross-section: A vertical-walled inner pit, usually with a nearly flat or concave floor, and a sloping outer funnel. The outer funnel is likely formed from material falling into the pit, driven by micrometeorite impacts. The relative sizes of these sections varies widely: compare the Lacus Mortis, Marius Hills, and Mare Recunditatis pits in the figure below.



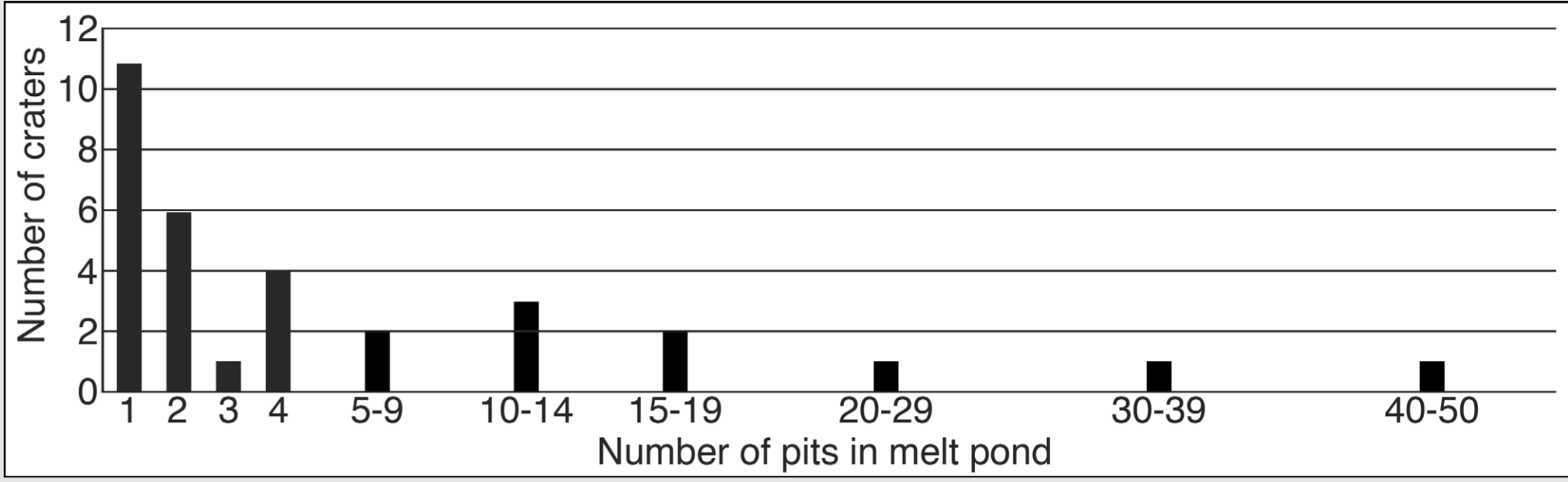
Above: Ten of the eleven known mare and highland pits, shown at the same scale. **Left:** New pit! Since the publication of [2] we have found one more mare pit, in Sinus Iridum (about 200 km from the Chang'e 3 landing site). At only about 8 m deep, it's not likely to connect to any extensive sublunarean voids, but it could still provide a clear view of layering in the upper meters of the mare.

Distribution Across the Moon



Map of the locations of all currently-known pits. Orange stars indicate mare or highland pits, and blue dots indicate craters with impact melt pits. 50° lines mark PitScan's search range.

Mare pits and impact melt pits are mostly distributed evenly around the Moon, within the area we have searched. The nine known mare pits occur across eight maria, and craters with impact melt pits show no bias toward occurring in mare or highland terrain. Pits do not generally occur in highland terrain outside of impact melt deposits.

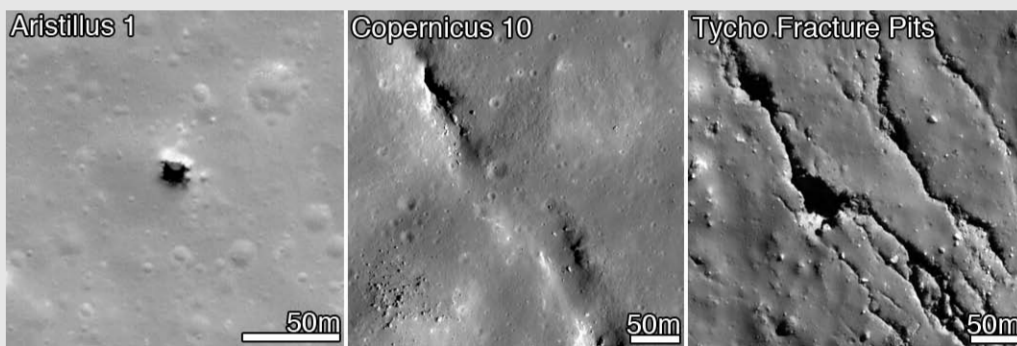


Above: Histogram of pits per crater. Most impact melt pits occur in just a few craters: King (50 pits), Tycho (35 pits), and Copernicus (26 pits) together contain more than half of the known impact melt pits. Note that in most cases the pit count for a crater is a minimum value, as most craters have not been fully searched for pits due to limitations of the available images.

Formation

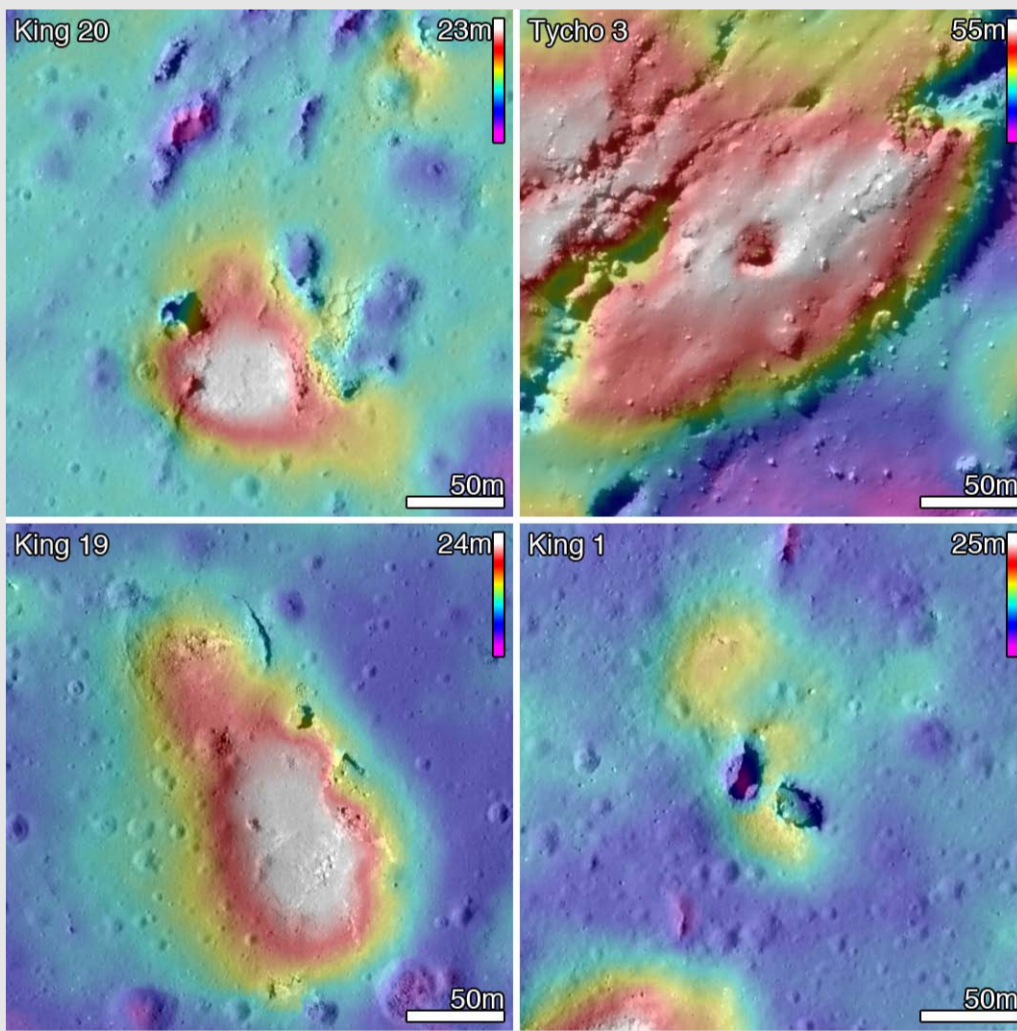
The existence of collapse pits implies the existence of sublunarean voids, which leads to the question of the origin of the voids. With only orbital data, it is difficult to come to a firm conclusion on this subject. A few mare and highland pits are near features that are suggestive of volcanic or tectonic origins (see figures to the left), but most have no diagnostic surface features nearby, and analysis of temperature and gravity data is inconclusive [3,4]. Given their location within maria, it is at least reasonable that most mare pits could be collapses into lava tubes, melt chambers, or other volcanically-formed voids.

Impact melt pits do show related morphology. The most frequent form of pit-like collapse in impact melts is a pit that is part of a larger linear fracture, and we thus call them “fracture pits”. These are not included in the count of >200 new pits, and it is difficult to draw a firm line between “fracture” and “fracture pit”. Non-fracture pits sometimes form within or in line with linear depressions or collapses, but this is uncommon. Like mare pits, the majority of impact melt pits have no nearby features to indicate a formation mechanism.



Above: Three types of pit that are found in impact melts. **Left:** Simple stand-alone pit, with no nearby features. **Center:** Pit in a linear depression. **Right:** Fracture pits and fractures.

Below: Examples of an unusual type of pit in King and Tycho craters, found in small positive relief features.



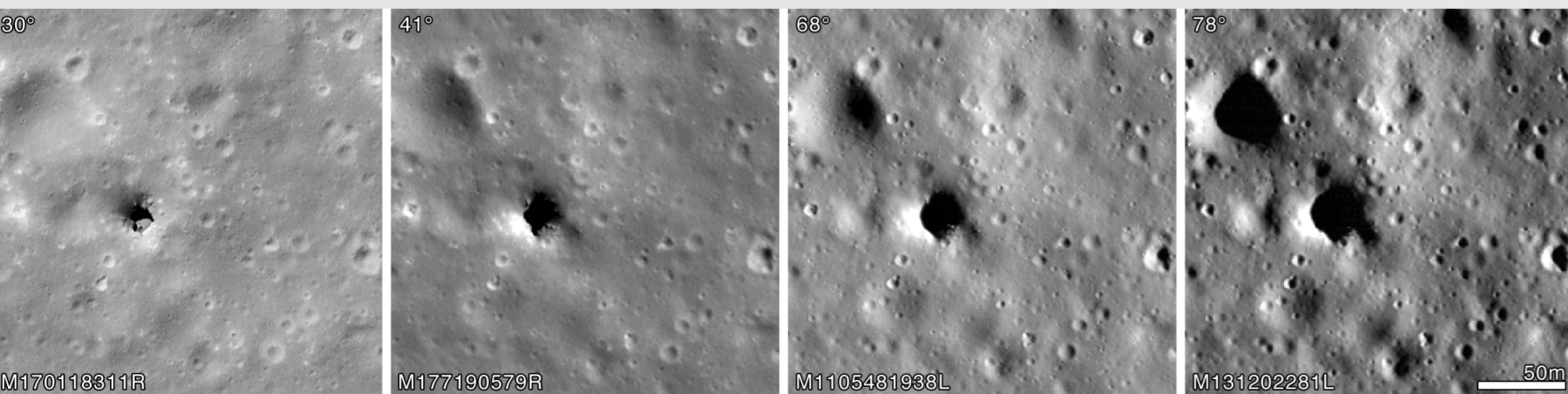
PitScan

To locate pits, we used a semi-automated search algorithm, which scans images for pit candidates, and creates 200x200 pixel clippings that a human can use to confirm if a feature is a pit. PitScan uses a three-step process:

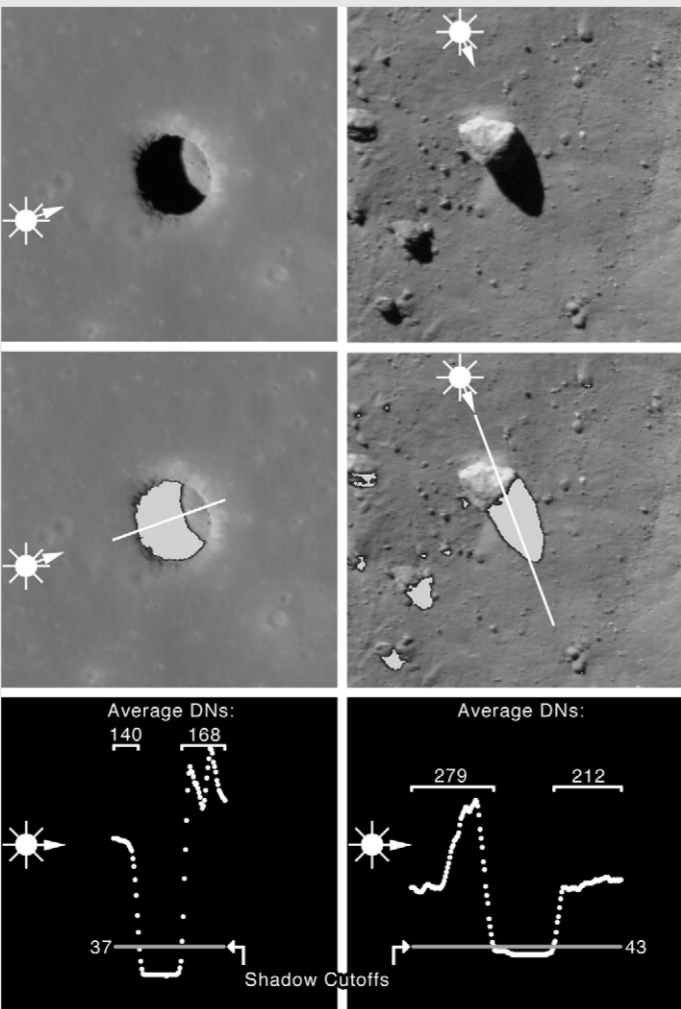
- 1) Determine a cut-off value for what is “shadowed” in the image.
- 2) Locate all blocks of "shadowed" pixels more than 10 pixels across.
- 3) For each such block of pixels, determine if the up-Sun or down-Sun side of the shadow is brighter. If the up-Sun side is brighter, then it is probably a rock, and should be ignored (see figure). Otherwise, save a small image of the shadow for classification by a human.

This method produces a large number of false positives (around 150 for each real pit), but it is fast, and due to the small number of pits, the total number of clippings a human needs to look through is relatively small. The ~25,000 high-Sun images from a six-month period take ~415 CPU-hours to process, and the output takes only a few hours for a human to sort through.

The main limitation of this algorithm is that when the Sun is less than ~40° above the horizon, crater walls can start casting shadows and being misclassified as possible pits, making the false positive rate too high. This restricts the area that PitScan can search for pits to within 50° of the equator.

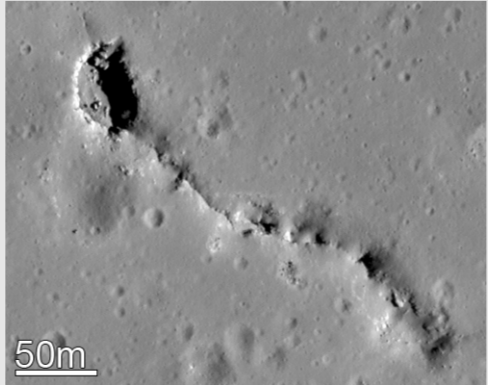


Above left: Comparison of a pit and crater in Palitzsch B at various incidence angles (Sun angle from zenith) ranging from 30° (far left) to 78° (far right), showing the difficulty of identifying pits in low-Sun images. **Above right:** Comparison of PitScan output for a pit (left) and a rock (right). Note the relative brightnesses of the up-Sun and down-Sun regions of the DN profiles (bottom panels).



Age Constraints

Neither the mare pits nor most of the impact melt pits are likely to have formed during the original emplacement of their host materials. The Mare Tranquillitatis pit (100 m diameter) and the Marius Hills pit (40 m) are both in maria with ages >3.3 Ga. From standard crater frequency distributions, craters on these surfaces should be in equilibrium at ~290 m [5], three times the diameter of the Mare Tranquillitatis pit, so it is exceedingly unlikely that small, crisp features such as these pits would have survived for >3 billion years. The mare pits likely formed from recent impacts breaching thin sections in the roofs of pre-existing sub-surface voids. A similar argument holds for impact melt pits. King and Copernicus craters, with two of the highest pit concentrations, are both ~1 billion years old, and have crater equilibrium diameters (measured from melt ponds) of 30-50 m [5,6]. Most of the pits on these melt sheets are <20 m in diameter, indicating that they would likely have been destroyed had they formed at the same time as the melt pond.



Left: A sharp-edged pit in the ~1 billion year old King crater melt pond, showing crisp edges with little debris on the floor. The depression extending to the lower right is likely due to material draining into a linear void space, perhaps triggered by impact events.

References

- [1] Haruyama et al. (2010). 41st LPSC #1285.
- [2] Wagner and Robinson (2014). Icarus, doi:10.1016/j.icarus.2014.04.002
- [3] Meyer and Hurtado (2012). 43rd LPSC #1636
- [4] Chappez et al. (2014). 45th LPSC #1746.
- [5] Hiesinger, H. et al. (2012), JGR, 117, doi:10.1029/2011JE003935.
- [6] Ashley, J.W. et al. (2012), JGR, 117, doi:10.1029/2011JE003990.

Conclusion

Mare pits reveal details about mare emplacement. The larger pits provide a 100 m deep cross-section through dozens of individual flows, and ground-level investigation could determine the late-stage eruption history of the maria, and perhaps even find solar wind particles that were trapped in the lunar surface billions of years ago (see poster 104 in Section X for details of our proposed "Arne" mission to explore a mare pit).

Exploring impact melt pits would pin down the nature of the voids in which they form. These voids are likely caused by melt flow within the pond after a crust has formed, driven by post-impact isostatic adjustments. Exploring these pits and their associated voids would help us understand the geologic behavior of large impact craters in the millennia after they form.

From a human activity perspective, both mare and impact melt pits would be useful in a support role. A habitat placed under an overhang in a pit, or in a deeper sublunarean void, would provide a very safe location for astronauts. There would be no radiation, no micrometeorites, possibly very little dust, and a stable thermal environment.

Right: Two possible pit destinations.

Left: An oblique view of the Mare Tranquillitatis pit, showing layering in the wall, and floor stretching back out of sight under an overhang. **Right:** A pit in Tycho crater with a smoothly-sloped “entry ramp” in its east wall, possibly allowing access by wheeled vehicles.

